

**Mountain Pine Beetle Impacts on Channel
Morphology and Woody Debris
in Forested Landscapes**

Marwan Hassan,¹ Dan Hogan,² Steve Bird,³

Mountain Pine Beetle Working Paper 2008-07

Natural Resources Canada, Canadian Forest Service,
Pacific Forestry Centre, 506 West Burnside Road, Victoria, BC V8Z 1M5
(250) 363-0600 • cts.nrcan.gc.ca/regions/pfc



Natural Resources
Canada

Ressources naturelles
Canada

Canada





Mountain Pine Beetle Impacts on Channel Morphology and Woody Debris in Forested Landscapes

Marwan Hassan,¹ Dan Hogan,² Steve Bird,³

Mountain Pine Beetle Working Paper 2008-07

MPBI Project # 8.40

¹ Department of Geography, 1984 West Mall, The University of British Columbia,
Vancouver, BC, V6T 1Z2

² BC Ministry of Forests and Range, The University of British Columbia, 2202 Main
Mall, Vancouver, BC, V6T 1Z4

³ Fluvial Systems Research Inc., No. 179, 106-1656 Martin Drive,
White Rock, B.C. V4A 6E7

Natural Resources Canada
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
2008

© Her Majesty the Queen in Right of Canada 2008
Printed in Canada

Library and Archives Canada Cataloguing in Publication

Hassan, Marwan

Mountain pine beetle impacts on channel morphology and woody debris in forested landscapes / Marwan Hassan and Dan Hogan.

(Mountain Pine Beetle Initiative working paper 2008-07)

Includes abstract in French.

"Mountain Pine Beetle Initiative, Canadian Forest Service".

"MPBI Project # 8.40".

Includes bibliographical references: p.

ISBN 978-0-662-48197-3

Cat. no.: Fo143-3/2008-7E

1. River channels--British Columbia. 2. Coarse woody debris--British Columbia. 3. Hydrology, Forest--British Columbia. 4. Riparian ecology--British Columbia. 5. Mountain pine beetle--British Columbia. I. Pacific Forestry Centre II. Title. III. Series.

SB945.M78H37 2008

551.3'53

C2008-980087-7

Abstract

In streams throughout British Columbia, woody debris affects channel geometry, the distribution of channel units, bed texture, bank stability, development of the riparian area, and diversity of aquatic habitat. Understanding changes in the woody debris budget (input, storage, and output) enables critical assessment of the impacts associated with the mountain pine beetle (MPB) on the hydrological and aquatic environment. The objective of this study is to determine watershed-scale impacts of MPB by comparing channel conditions and the woody debris budget in watersheds infested by the MPB with those from similar old-growth forests with pre-infestation channel and riparian data. The use of a woody debris budget directly links large-scale lodgepole pine mortality to stream channel and riparian processes and conditions at the landscape level. Eighteen watersheds in the Sub-Boreal Spruce and Sub-Boreal—Pine Spruce biogeoclimatic zones were considered. The results are used to generate regionally and locally relevant best management practices that will guide operational planning in landscapes impacted by the MPB.

The effect of the MPB infestation on channel processes and morphology will largely depend on the response and recovery of woody debris. Although the MPB infestation is now considered at epidemic levels across the landscape, riparian areas surveyed in this report support relatively small volumes of lodgepole pine (if any). In comparison to the volume of wood transferred to the channel during a stand-replacing event, wood transfer to the channel induced by MPB infestation in the next 25 years is likely to be relatively small and within the range of typical conditions throughout the region. In riparian areas with a similar distribution of lodgepole pine in the riparian area, management for the riparian supply of woody debris to small channels in areas infested by MPB may be effectively undertaken using existing regulations and guidelines of the Forest and Range Practices Act, and evaluations undertaken as part of the Forests and Range Evaluation Program.

Keywords: mountain pine beetle, watershed impacts, stream channels, woody debris budgets

Résumé

Dans les cours d'eau de la Colombie-Britannique, des débris ligneux ont des effets sur la géométrie des chenaux, la distribution des unités de chenal, la texture du lit, la stabilité des berges, le développement des bandes riveraines et la diversité des habitats aquatiques. Une bonne compréhension des changements du bilan des débris ligneux (entrée, stockage et sortie) permet une évaluation cruciale des répercussions du dendroctone du pin ponderosa (DPP) sur l'environnement hydrologique et aquatique. La présente étude a pour objet de déterminer les répercussions du DPP à l'échelle du bassin hydrologique en comparant les états des chenaux ainsi que le bilan des débris ligneux des bassins hydrologiques infestés par le DPP à celui de forêts anciennes semblables pour lesquelles nous avons des données riveraines et fluviales préinfestation. L'utilisation d'un bilan des débris ligneux établit un lien direct entre la mortalité à grande échelle de pins tordus et les

conditions et processus fluviaux et riverains à l'échelle du paysage. Dix-huit bassins hydrologiques en zones biogéoclimatiques subboréales à épinette et à épinette et pin ont été considérés. Les résultats servent à élaborer des pratiques de gestion exemplaires, tant à l'échelle locale qu'à l'échelle régionale, qui guideront la planification opérationnelle des territoires affectés par le DPP.

L'effet de l'infestation de DPP sur les processus et la morphologie des chenaux dépendra en bonne partie de la récupération des débris ligneux. Bien que l'on considère l'infestation de DPP comme une épidémie, les zones riveraines examinées dans le cadre du présent rapport comportent des quantités relativement faibles de pin tordu (lorsqu'il y en a). Comparé au volume de bois transféré au chenal pendant un événement de remplacement de peuplement, le transfert de bois causé par une infestation de DPP au cours des 25 prochaines années est susceptible d'être relativement petit et dans une échelle qui correspond aux conditions normales dans l'ensemble de la région. Dans les zones riveraines avec une distribution comparable de pin tordu, la gestion du transfert de débris ligneux dans des petits chenaux de régions infestées par le DPP peut être entreprise efficacement à l'aide des règlements et des lignes directrices existantes de la *Forest and Range Practices Act* de la Colombie-Britannique et des évaluations réalisées dans le cadre du Forest and Range Evaluation Program (*programme d'évaluation des forêts et des montagnes*).

Mots-clés : dendroctone du pin ponderosa, répercussions sur les bassins hydrologiques, chenaux de cours d'eau, bilans des débris ligneux.

Table of Contents

1.0	Introduction.....	7
2.0	Watershed Selection and Disturbance History	8
2.1	Watershed Comparisons	8
2.1.1	Method of Comparison	8
2.1.2	Biophysical Similarity of Study Watersheds	10
2.1.3	Morphometric Similarity of Study Channels	15
2.1.4	Selection of Watershed Triplets	17
2.2	Disturbance History	18
2.2.1	Flood	18
2.2.2	Landslide	19
2.2.3	Mountain Pine Beetle (MPB) Infestation	20
3.0	Methods.....	20
4.0	Results and Discussion	21
4.1	Riparian forest characteristics.....	21
4.2	Riparian Woody Debris Recruitment.....	24
4.3	Woody Debris Budget.....	30
4.4	Jam frequency	32
5.0	Conclusions.....	34
6.0	Acknowledgements.....	35
7.0	Literature Cited	35

List of Tables

Table 1. Map-based biophysical parameters and criteria used to identify geographic areas with similar climate, soils, and vegetations.	11
Table 2. Biophysical characteristics of each study region.	12
Table 3. Fourteen (14) variables chosen to describe and compare the morphometry of the 18 watersheds surveyed for this study.	13
Table 4. Dissimilarity matrix describing the Euclidean distance amongst watersheds based on the 14 variables described in Table 3.	14
Table 5. Six variables chosen to describe and compare the morphometry of channel reaches in the 18 watersheds surveyed for this study.	15
Table 6. Dissimilarity matrix describing the Euclidean distance amongst channels based on the six variables described in Table 5.	16
Table 7. Morphometric basin and channel dissimilarity amongst watershed triplets.	17
Table 8. Summary of the ANOVA used to test for differences amongst a) basin and b) channel dissimilarity in each study region.	18
Table 9. Discharge magnitude by return period for select Water Survey of Canada gauging stations near the study regions.	19
Table 10. Years in which a reference discharge was exceeded for gauging stations listed in Table 8 during the period of study (1998 or 1999 to 2005).	19
Table 11. MPB infestation in the study basins.	21
Table 12. Riparian forest characteristics adjacent to the study channels.	23
Table 13. Distribution of lodgepole in the riparian forest adjacent to the study channels (as surveyed in 2006).	25
Table 14. Maximum tree age used to estimate the probability of tree mortality in a given year.	26
Table 15. The rate of woody debris input to each channel in the SBPS zone.	29
Table 16. Chi-square analysis of the frequency of log jams in the six control watersheds (expected values are given in parentheses).	32
Table 17. Summary of the two factor ANOVA used to test for differences in log jam frequencies between biogeoclimatic zones and study regions (and the interaction between both groups).	34

List of Figures

Figure 1. Study site locations.	9
Figure 2. Storage volumes of woody debris following MPB infestation in streams of the SBPS.	33

1.0 INTRODUCTION

In small streams throughout forested regions of British Columbia, woody debris is introduced to the stream channel through a variety of processes including mass wasting, tree fall (blowdown), bank erosion, and floatation from upstream. Once in the channel boundary, both fluvial and non-fluvial processes transport and redistribute wood to downstream locations in the drainage network (e.g., Keller and Swanson 1979, Lienkaemper and Swanson 1987, Nakamura and Swanson 1994, Hogan et al. 1998a, Johnson et al. 2000, Benda et al. 2002, Benda et al. 2003). Woody debris within the channel boundary significantly alters flow hydraulics, regulates sediment transport and storage, and influences channel morphology (e.g., Hogan 1986, Bisson et al. 1987, Montgomery et al. 1996). In-channel wood also plays an important role in determining aquatic habitat conditions, diversity of channel habitat, and riparian ecology (e.g., Bisson et al. 1987, Bilby and Bisson 1998). In general, wood exerts its greatest geomorphic influence in channels with physical dimensions similar to or smaller than the size of wood (Bilby and Ward 1989, Bilby and Bisson 1998); therefore, wood plays a disproportionately larger role in smaller streams.

British Columbia is in the midst of a mountain pine beetle (MPB) (*Dendroctonus ponderosae*) epidemic, with approximately 8.7 million ha of forest infested as of 2005 (BC Ministry of Forests and Range 2005). Lodgepole pine (*Pinus contorta* var. *latifolia*) is the main host of MPB (beetle-host interactions are summarized by Safranyik and Carroll 2006), with typical tree mortality rates by number of stems in a stand in the range of 25 to 50% (Shore et al. 2006). The outbreak is likely to continue until 2014 or 2015, with 80% of pine volume in stands having >10% pine killed by 2013 (Eng et al. 2006).

The MPB infestation may affect channel morphology and aquatic habitat in lodgepole pine forests by altering the quality (species, integrity, size) and quantity of woody debris recruited to the channel network over the next century. Following MPB infestation in a watershed, a rapid but short-term increase in recruitment rates of woody debris is expected as mature trees die and are transferred to the channel. This may lead to the development of relatively frequent and impermeable log jams, where riffles that serve as spawning areas are either buried or eroded (upstream and downstream of a jam, respectively), rearing pools are in-filled and egg incubation environments are smothered with fine-textured sediments (Hogan et al. 1998b). Following this initial phase, a prolonged decrease in recruitment rates is expected, as woody debris sources are restricted to relatively small, immature trees. As stored woody debris is depleted from a channel and replaced by relatively small logs, the mobility of woody debris is expected to increase. In turn, this is likely to increase long-term rates of sediment transport, as less sediment is stored behind woody debris (especially log jams).

The objectives of this report are to determine the input, storage, and output rates of woody debris supplied to small streams located in watersheds infested by MPB, and then assess the impact(s) of any changes in woody debris dynamics on channel morphology. These results will directly link large-scale lodgepole pine mortality to stream channel and riparian processes and conditions at the landscape level through use of a woody debris

budget. The input terms of the budget (e.g., rate of lodgepole pine mortality tallied by basal area) will be manipulated to examine long-term changes in woody debris dynamics following MPB infestation and assess changes in channel and riparian conditions. The woody debris budget will also provide a link to existing landscape-scale models that predict impacts (percent basal area killed) in the event of MPB infestation (e.g., Shore et al. 2000).

2.0 WATERSHED SELECTION AND DISTURBANCE HISTORY

Six watersheds in the SBS and SBPS biogeoclimatic zone were selected for analysis (Figure 1). These watersheds were originally surveyed in either 1998 or 1999, prior to MPB infestation, and then resurveyed in 2006. Watersheds were selected to represent a variety of terrain-types typical of the Interior Plateau and the Northern and Central Plateaus and Mountains physiographic regions. Each before-after comparison was supplemented with surveys completed in two additional watersheds, representing post-treatment watershed triplets used to assess the spatial variability of channel conditions following MPB infestation.

2.1 Watershed Comparisons

2.1.1 Method of Comparison

The character of a stream channel develops primarily as a function of the flood and sediment regime, the materials that comprise the channel boundary and near-channel environment, and the geological history of the watershed (Church 1992), and ultimately depends on the biophysical properties of a watershed. In a paired-watershed study design, a measured difference in some channel attributes can only be associated with a treatment if all other factors that influence the attribute are alike. Although no two channels are identical, the confounding influence of the biophysical setting of a watershed can be minimized if differences are known and accounted for in subsequent analysis.

Rodda (1976) considers two watersheds biophysically similar if climate, soils, vegetations, and morphometry are similar. Hogan (1986) used these criteria to study the influence of logging and mass wasting on channel morphology in six watershed pairs on the Queen Charlotte Islands. Both dimensional (e.g., drainage density, mean elevation, etc.) and dimensionless (e.g., mean slope, hypsometric interval, etc.) morphometric parameters were selected for analysis. Dimensional and dimensionless parameters were converted to linear scale ratios and dimensionless number ratios, respectively, by dividing the unlogged watershed value by the logged or tormented watershed value. Morphometric parameters were considered similar amongst watersheds if the morphometric ratios did not differ by more than one standard deviation. Watershed pairs were then selected following a qualitative review of each parameter.

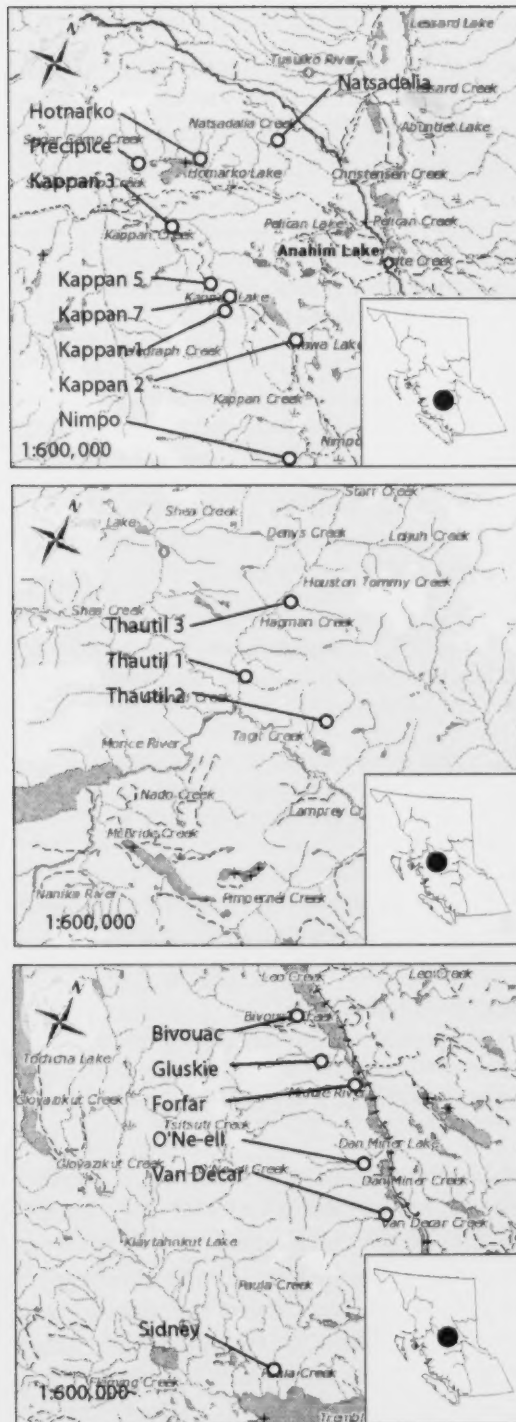


Figure 1. Study site locations.

Cheong (1992) developed a method of watershed comparison that quantifies the comparison amongst watershed pairs. The method is similar to that used by Hogan (1986), although the subjective selection of watershed pairs is eliminated and replaced by a dissimilarity index. The Euclidean distance between each potential watershed pair is based on

$$d_{ij}^{(\lambda)} = \left[\frac{\sum_{k=1}^p w_k |x_{ik} - x_{jk}|}{\sum_{k=1}^p w_k} \right]^{1/\lambda} \quad [\text{Eq. 1}]$$

where w_k ($k = 1 \dots p$) is a set of weights, i represents the first object, j represents the second object, k is the k^{th} characteristic, $\lambda > 0$ and higher values of λ give relatively more emphasis to larger differences $|x_{ik} - x_{jk}|$ (Gordon 1981, Cheong 1992). When $\lambda = 2$, one has the weighted root mean square. The dissimilarity between any two objects increases as $d_{ij}^{(\lambda)}$ increases. Cheong (1992) suggests variables with a relatively large range of variation may skew dissimilarity calculations and gives the standardized form of the Euclidean distance

$$d_{ijk}^2 = \frac{[x_{ik} - x_{jk}]^2}{\sigma_k^2} \quad [\text{Eq. 2}]$$

where σ is the standard deviation of a given morphometric parameter calculated amongst all watersheds in the sample. Once dissimilarity values are calculated for each parameter, the total dissimilarity is determined by the square root of the sum of all dissimilarity values calculated for each parameter [Eq. 1].

2.1.2 Biophysical Similarity of Study Watersheds

The climate, soils, and vegetations in each of the six watersheds originally surveyed in either 1998 or 1999 were described from a series of map-based measurements and used to define a geographic area from which candidate watersheds could be selected. A description of each criterion is given in Table 1 with results given in Table 2. Within each study region, candidate watersheds were tested for morphometric similarity if a reach at the outlet of the watershed flowed through the appropriate biogeoclimatic zone. Fourteen (14) variables were chosen to describe and compare the morphometry of the 18 watersheds surveyed for this study (Table 3). The variables were selected based on preliminary work undertaken by Cheong (1993) given their relation to hydrological and geomorphological processes operating within a watershed (cf. Zavoianu 1985, Cheong 1992). The dissimilarity amongst watersheds is given in Table 4.

Table 1. Map-based biophysical parameters and criteria used to identify geographic areas with similar climate, soils, and vegetations.

Biophysical parameter	Scale	Criteria and description	Source
Physiographic zone	1:5,000,000	Five zones with similar landforms resulting from similar processes of erosion and deposition, similarities of bedrock response to erosion, and similarities of orogenic history. Watershed triplets were in the same zone.	Holland (1965)
Hydrologic zone	1:7,000,000	Ten zones with similar hydroclimatic conditions. Watershed triplets were in the same zone.	Church (1997)
<i>k</i> -factor	1:12,500,000	A scale-independent runoff-factor for the mean annual flood. Watershed triplets were within ± 0.1 of one another.	Eaton et al. (2002)
Vegetation cover	1:1,000,000	Proportion of unvegetated cover may influence the infiltration rate, runoff patterns, soil development, snow pack, snowmelt, and the hydrological response of a watershed. Watershed triplets were within ± 0.1 of one another.	Agriculture and Agri-Food Canada (1996)
Hard rock	1:1,000,000	Proportion of surface material classified as hard rock may influence vegetation patterns, disturbance regimes (i.e., landslide history), dominant erosion mechanisms, hydrological response, and infiltration rate and runoff patterns. Watershed triplets were within ± 0.1 of one another.	Agriculture and Agri-Food Canada (1996)
Drainage class	1:1,000,000	Dominant and/or subdominant drainage class (e.g., rapid, well, moderately well, poor, and very poor) may be related to slope stability, infiltration rate, runoff patterns, hydrological response, and soil characteristics. Watershed triplets were in the same dominant or subdominant drainage class.	Agriculture and Agri-Food Canada (1996)
Soil type	1:1,000,000	Soil properties are determined by climatic factors and organisms, as conditioned by the relief and the moisture regime acting on geological materials. Watershed triplets were characterized by the same dominant or subdominant Great Group.	Agriculture and Agri-Food Canada (1996)
Geology	1: 250,000	Five general rock-types (Quaternary, volcanic, sedimentary, intrusive, and metamorphic) may influence rates of erosion, sediment production (quality and quantity), and slope stability. Watershed triplets were characterized by the same dominant or subdominant rock-type.	BC Geological Survey (1997)
Biogeoclimatic zone	1: 20,000 to 1:600,000	Fourteen zones group together ecosystems with similar climate, soils and vegetation at the broad landscape level. Watershed triplets were in the same zone at the outlet of the watershed.	BC Ministry of Forests (2003)

Table 2. Biophysical characteristics of each study region (refer to Table 1 for definitions). Sub-dominant parameters are given in parentheses where appropriate. Each study region is named after the control watershed originally surveyed in either 1998 or 1999.

Parameter	Study Region					
	Hotnarko	Precipice	Kappan	Thautil	O'Ne-el	Forfar
Physiographic zone	Interior Plateau	Interior Plateau	Interior Plateau	Interior Plateau	Northern & Central Plateaus & Mountains	Northern & Central Plateaus & Mountains
Hydrologic zone	Chilcotin/Cariboo Plateau	Chilcotin/Cariboo Plateau	Chilcotin/Cariboo Plateau	Northern Interior	Northern Interior	Northern Interior
k-factor	0.5	0.5	0.5	1.3	0.5	0.5
Vegetation cover	1.0	1.0	1.0	1.0	1.0	1.0
Hard rock	0.0	0.0	0.0	0.0	0.0	0.0
Drainage class	Rapid to well drained	Rapid to well drained	Rapid to well drained	Well drained	Well drained	Well drained
Soil type	Dystric Brunisolic (Mesisol)	Dystric Brunisolic (Mesisol)	Dystric Brunisolic (Mesisol)	Humo-Ferric Podzolic	Humo-Ferric Podzolic	Humo-Ferric Podzolic
Geology	Volcanic (alluvium or till)	Volcanic (intrusive)	Volcanic (intrusive)	Volcanic (sedimentary)	Sedimentary (intrusive)	Intrusive (sedimentary)
Biogeoclimatic zone & subzone	SBPSxc	SBPSxc	SBPSxc	SBSmc	SBSwk	SBSwk

Table 3. Fourteen (14) variables chosen to describe and compare the morphometry of the 18 watersheds surveyed for this study. Planimetric and elevation data was obtained from 1:20,000 TRIM maps and 25 m gridded DEMs, respectively.

Watershed	Basin area (km ²)	Basin perimeter (km)	Ice Cover (km ²)	Lake cover (km ²)	Steepland area (km ²)	Valley flat area (km ²)	Mean gradient ^a (m/m)	Mean elevation ^b (m)	Main channel length ^c (km)	Magnitude	Drainage density (km/km ²)	Relief (m)	Shape factor ^d (km ² /km ²)	Main channel gradient (m/m)
<i>Thautil study region</i>														
Thautil 1	11.0	20.0	0.0	0.1	0.0	0.3	0.19	1212	7.8	6	1.4	602	5.5	0.072
Thautil 2	12.7	19.0	0.0	0.1	0.0	0.2	0.17	1166	7.3	7	1.3	643	4.2	0.068
Thautil 3	9.1	15.7	0.0	0.1	0.0	0.3	0.21	1155	6.2	22	2.4	743	4.2	0.104
<i>O'Ne-el study region</i>														
O'Ne-el	43.0	39.0	0.0	0.7	0.8	2.1	0.2	1276	13.9	73	2.0	1256	4.5	0.073
Bivouac	42.2	43.2	0.0	0.7	0.2	3.4	0.17	1166	19.2	65	2.0	844	8.7	0.030
Sidney	37.1	33.1	0.0	0.2	1.1	1.2	0.26	1265	10.0	71	2.5	1100	2.7	0.073
<i>Forfar study region</i>														
Forfar	37.8	38.1	0.0	0.3	2.9	1.5	0.29	1321	16.1	46	1.7	1319	6.8	0.065
Gluskie	47.2	37.3	0.0	0.4	3.7	2.8	0.29	1324	15.3	64	1.8	1285	5.0	0.029
Van Decar	26.8	30.8	0.0	0.2	1.3	0.8	0.24	1380	11.4	32	1.9	1293	4.8	0.095
<i>Hotnarko study region</i>														
Hotnarko	7.1	16.2	0.0	0.1	0.0	0.0	0.09	1416	6.5	10	2.6	460	6.0	0.056
Kappan 4	5.9	12.5	0.0	0.1	0.0	0.7	0.19	1471	4.6	15	2.6	933	3.7	0.085
Kappan 5	10.1	16.7	0.0	0.2	0.0	3.3	0.11	1357	6.5	15	2.1	647	4.2	0.064
<i>Precipice study region</i>														
Precipice	10.6	15.3	0.0	0.0	0.0	0.1	0.17	1596	6.9	8	1.1	885	4.5	0.115
Nimpo	8.5	14.8	0.0	0.1	0.0	3.2	0.07	1432	6.4	3	0.9	314	4.8	0.038
Kappan 3	4.6	12.8	0.0	0.0	0.0	0.3	0.19	1475	5.2	5	1.6	842	5.8	0.138
<i>Kappan study region</i>														
Kappan 1	8.4	13.7	0.0	0.2	0.0	2.5	0.12	1382	4.9	11	1.9	569	2.8	0.069
Natsadalia	7.2	22.2	0.0	0.4	0.0	4.8	0.05	1325	9.1	6	2.6	394	11.5	0.025
Kappan 2	13.3	18.4	0.0	0.5	0.1	2.8	0.16	1333	10.0	32	2.7	658	7.6	0.050

^a Mean basin gradient

^b Mean basin elevation

^c The main channel is described by the longest, highest order series of channel links extending from the basin outlet to the headwaters

^d Squared length of the main channel divided by the drainage area

Table 4. Dissimilarity matrix describing the Euclidean distance amongst watersheds based on the 14 variables described in Table 3. The most similar watershed pairs were Thautil 1 and Thautil 2 creeks with a dissimilarity value of 0.90. The most dissimilar watershed pairs were Precipice and Bivouac creeks with a dissimilarity value of 8.52.

Watershed ^a	T1	T2	T3	O	G	V	B	S	F	H	N	NI	K2	K5	K3	P	K1	K4
T1	0.00	0.90	2.55	6.37	7.08	3.90	6.82	5.45	5.75	3.19	5.69	3.73	4.16	3.51	3.39	3.78	2.99	3.16
T2		0.00	2.72	6.36	7.17	4.15	6.94	5.51	5.99	3.62	6.10	3.75	4.54	3.84	3.82	4.06	3.01	3.28
T3			0.00	5.95	7.14	3.82	7.03	4.53	5.96	3.55	6.31	5.39	3.94	2.93	3.59	4.63	3.33	3.45
O				0.00	3.65	3.98	3.40	2.98	3.55	7.02	7.50	7.66	4.89	6.47	7.29	7.20	6.42	5.95
G					0.00	4.52	4.81	3.98	2.29	7.85	8.16	8.10	5.99	7.32	8.21	7.95	7.33	6.88
V						0.00	5.77	3.17	2.96	4.86	6.87	5.87	4.34	3.76	4.14	4.11	4.50	4.31
B							0.00	5.20	4.69	7.43	6.23	7.72	4.82	7.83	8.52	8.52	7.27	6.50
S								0.00	3.79	6.00	7.74	7.23	4.78	5.10	6.35	6.43	5.56	5.30
F									0.00	6.83	7.50	7.40	5.31	6.29	6.68	6.57	6.60	6.18
H										0.00	4.74	3.87	3.52	2.70	3.83	4.15	2.75	2.81
N											0.00	4.99	3.45	6.12	6.76	7.19	5.13	4.27
NI												0.00	4.88	4.69	4.76	4.26	2.76	2.88
K2													0.00	3.89	5.16	5.61	3.58	2.83
K5														0.00	2.77	3.22	2.50	2.84
K3															0.00	1.86	3.58	3.96
P																0.00	3.69	4.16
K1																	0.00	1.11
K4																		0.00

^a Abbreviations: T1 = Thautil 1; T2 = Thautil 2; T3 = Thautil 3; O = O'Ne-el; G = Gluskie; V = Van Decar; B = Bivouac; S = Sidney; F = Forfar; H = Hotnarko; N = Natsadalia; NI = Nimpo; K2 = Kappan 2; K5 = Kappan 5; K3 = Kappan 3; P = Precipice; K1 = Kappan 1; K4 = Kappan 4.

2.1.3 Morphometric Similarity of Study Channels

A description and quantification of the biophysical properties of a watershed is an effective tool for describing the general character of a watershed and can be used to infer the dominance of certain watershed processes and their influence on channel morphology. However, watersheds with similar biophysical properties may not always have similar stream channels (e.g., Hogan et al. 1998a). In particular, local controls of channel gradient, such as an outcrop of bedrock or a tributary confluence, can affect subtle changes in channel processes and alter the expected morphology.

The next step in the selection process was a description and quantitative comparison of stream reaches within the candidate watersheds. Six parameters were selected to describe the general size and shape of a channel (Table 5). These data were either on an interval or ratio scale and are relatively independent of the presence of functional woody debris in a channel (e.g., functional woody debris may influence the variability amongst width and depth, but do not usually effect the overall mean width and depth). The dissimilarity amongst reaches was calculated after Eq. [1] and [2] and is given in Table 6.

Table 5. Six variables chosen to describe and compare the morphometry of channel reaches in the 18 watersheds surveyed for this study.

Watershed	Width (m)	Depth (m)	D_{50} (mm)	Slope (m/m)	Shape^a (m/m)	Roughness^b (m/m)
<i>Thautil study region</i>						
Thautil 1	4.1	0.53	25	0.0457	0.59	0.19
Thautil 2	4.3	0.83	31	0.0308	0.65	0.12
Thautil 3	3.2	0.38	21	0.0465	0.56	0.18
<i>O'Ne-el study region</i>						
O'Ne-el	14.0	0.64	32	0.0144	0.62	0.14
Bivouac	8.0	0.74	29	0.0302	0.60	0.13
Sidney	7.3	0.64	20	0.0208	0.61	0.10
<i>Forfar study region</i>						
Forfar	11.1	0.67	23	0.0078	0.57	0.10
Gluskie	11.2	0.60	35	0.0124	0.65	0.15
Van Decar	10.5	0.67	26	0.0121	0.59	0.11
<i>Hotmarko study region</i>						
Hotmarko	2.5	0.27	32	0.0426	0.51	0.35
Kappan 4	2.4	0.35	17	0.0752	0.49	0.14
Kappan 5	1.6	0.24	21	0.0615	0.40	0.27
<i>Precipice study region</i>						
Precipice	3.1	0.49	31	0.0240	0.55	0.16
Nimpo	1.4	0.30	17	0.0259	0.37	0.18
Kappan 3	1.9	0.51	40	0.0335	0.48	0.23
<i>Kappan study region</i>						
Kappan 1	1.9	0.24	12	0.0137	0.58	0.15
Natsadalia	2.2	0.38	22	0.0277	0.42	0.17
Kappan 2	1.7	0.32	21	0.0279	0.42	0.19

^a Hydraulic radius/depth of maximum flow (see Hey 1979)

^b D_{50} /mean channel depth

Table 6. Dissimilarity matrix describing the Euclidean distance amongst channels based on the six variables described in Table 5. The most similar channel pairs were Forfar and Van Decar creeks with a dissimilarity value of 0.44. The most dissimilar channel pairs were Forfar and Kappan 5 creeks with a dissimilarity value of 5.55.

Watershed ^a	T1	T2	T3	O	G	V	B	S	F	H	N	NI	K2	K5	K3	P	K1	K4
T1	0.00	2.23	0.90	3.15	2.73	2.82	1.91	2.28	3.19	3.12	2.43	3.12	2.52	2.36	1.60	1.40	2.53	3.14
T2		0.00	2.95	2.79	2.38	2.15	1.23	1.51	2.48	5.10	3.77	4.51	4.03	4.05	3.14	2.28	3.52	5.21
T3			0.00	3.60	3.16	3.25	2.58	2.70	3.56	2.82	1.99	2.58	1.98	1.91	1.53	1.44	2.08	2.56
O				0.00	0.83	1.01	1.80	1.80	1.15	5.22	4.04	4.66	4.26	4.87	3.81	2.92	3.69	5.55
G					0.00	0.95	1.59	1.44	1.25	4.84	3.75	4.40	3.93	4.64	3.43	2.40	3.08	5.31
V						0.00	1.27	1.00	0.44	5.15	3.48	4.14	3.76	4.54	3.34	2.30	3.21	5.31
B							0.00	0.97	1.64	4.66	3.23	3.97	3.51	3.72	2.75	1.92	3.23	4.71
S								0.00	1.25	4.99	3.17	3.88	3.47	3.91	3.02	1.78	2.76	4.98
F									0.00	5.46	3.62	4.24	3.92	4.78	3.62	2.56	3.37	5.55
H										0.00	3.22	3.33	2.88	3.82	2.47	3.49	3.67	2.17
N											0.00	0.75	0.45	2.83	1.40	1.72	2.17	2.52
NI												0.00	0.66	3.18	1.95	2.43	2.57	2.44
K2													0.00	2.88	1.39	1.89	2.13	2.25
K5														0.00	2.81	3.04	3.62	2.43
K3															0.00	1.46	2.44	2.43
P																0.00	1.56	3.50
K1																	0.00	3.80
K4																		0.00

^a Abbreviations: T1 = Thautil 1; T2 = Thautil 2; T3 = Thautil 3; O = O'Ne-el; G = Gluskie; V = Van Decar; B = Bivouac; S = Sidney; F = Forfar; H = Hotnarko; N = Natsadalia; NI = Nimpo; K2 = Kappan 2; K5 = Kappan 5; K3 = Kappan 3; P = Precipice; K1 = Kappan 1; K4 = Kappan 4.

2.1.4 Selection of Watershed Triplets

The final selection of watershed triplets was made by grouping watersheds by study regions and then selecting triplets that minimize the dissimilarity amongst both watershed- and channel-scale morphometrics. The results are given in Table 7. Watershed dissimilarities range between 0.90 and 5.20, while channel dissimilarities range between 0.45 and 3.82. The amount of dissimilarity measured in each group was compared with a single factor ANOVA and it was concluded that there was no difference amongst study regions given the watershed or channel characteristics used in this study (Table 8). This suggests that although the watersheds and channels were characterized by some morphometric differences, these differences were present in all study regions and were of similar magnitude (i.e., watershed triplets are equally dissimilar in each region). Given this rigorous, quantitative selection process, it is concluded that the potential bias introduced by biophysical differences amongst watersheds has been minimized, and that differences in channel behavior and response to MPB disturbance are similar within each study region (i.e., the chances of committing a Type I error as a result of watershed and channel dissimilarity are similar in each study region).

Table 7. Morphometric basin and channel dissimilarity amongst watershed triplets.

Study region	Watershed comparison	Dissimilarity	
		Basin	Channel
Thautil	Thautil 1 vs. Thautil 2	0.90	0.90
	Thautil 1 vs. Thautil 3	2.55	2.23
	Thautil 2 vs. Thautil 2	2.72	2.95
O'Ne-el	O'Ne-el vs. Bivouac	3.40	1.80
	O'Ne-el vs. Sidney	2.98	1.80
	Bivouac vs. Sidney	5.20	0.97
Forfar	Forfar vs. Gluskie	2.29	1.25
	Forfar vs. Van Decar	2.96	0.44
	Gluskie vs. Van Decar	4.52	0.95
Hotnako	Hotnarko vs. Kappan 4	2.81	3.82
	Hotnarko vs. Kappan 5	2.70	3.22
	Kappan 4 vs. Kappan 5	2.84	0.45
Precipice	Precipice vs. Nimpo	4.26	2.43
	Precipice vs. Kappan 3	1.86	1.46
	Nimpo vs. Kappan 3	4.76	1.95
Kappan	Kappan 1 vs. Natsadalia	5.13	2.52
	Kappan 1 vs. Kappan 2	3.58	2.25
	Natsadalia vs. Kappan 2	3.45	0.45

Table 8. Summary of the ANOVA used to test for differences amongst a) basin and b) channel dissimilarity in each study region. In both cases the null hypothesis was accepted, suggesting that watersheds and channels were equally dissimilar in each study region.

Source of variation	SS	DF	MS
<i>a) Watershed dissimilarity</i>			
Total	23.36	17	
Groups	8.40	5	1.68
Error	13.96	12	1.16
<i>b) Channel dissimilarity</i>			
Total	16.86	17	
Groups	4.44	5	0.89
Error	12.42	12	1.04

a) $F_{05(1), 5, 12} = 3.11$, $F = 1.44$, $F_{crit} < F$ therefore accept H_0

b) $F_{05(1), 5, 12} = 3.11$, $F = 0.86$, $F_{crit} < F$ therefore accept H_0

2.2 Disturbance History

The success of the before-after assessment of channel conditions depends in part on the disturbance history in each watershed before and after treatment. Initial channel disturbance and subsequent recovery from an extreme event (e.g., flood, landslide, etc.) could confound channel response to MPB infestation. Riparian areas were unlogged at the time of survey.

2.2.1 Flood

Streamflow data is generally not available for the study watersheds (although WSC gauge 08ED004 has operated on Thautil 1 since 1998). However, mean and maximum annual daily flows have been recorded at several neighbouring watersheds and these data are used here to approximate the flood history of the study watersheds. Gauges were selected for analysis given the following criteria: gauges were in the same hydrologic region (as defined by Church 1997) and were < 200 km from the respective study watershed; drained an area of < 500 km²; were not situated at the outlet of a lake; maintained a record over the study period from 1998 to 2005; and, had a record long enough to permit flood frequency analysis (preferably > 20 years of record although some exceptions were made given the scarcity of data).

Gauging stations selected for analysis are given in Table 9. Annual maximum daily discharges for the respective periods of record were plotted on Gumble paper. The discharge values for a given return period were extrapolated and the years in which these values were exceeded are given in Table 10. Seven gauging station records were available for application to the Thautil, Forfar, and O'Ne-el study regions. The most prominent flood event in these watersheds occurred in 2002 when the mean annual flow ($Q_{2.33}$) was exceeded in all stations selected for analysis, and exceeded a 10-year return period (Q_{10}) in four of seven stations. It is assumed here that channels in this study region were affected by a flood in 2002 with a magnitude $> Q_{10}$ but $\leq Q_{50}$ that had a significant impact on channel morphology (i.e., mobilized bed material sediments and woody debris, induced localized bank erosion, and created or rearranged log jams). Only two gauging station records were available for application to the Precipice, Hotnarko, and Kappan

study regions, and estimates made for these regions with a relatively high level of uncertainty. In both stations, $Q_{2.33}$ was exceeded in 2002, 2003, and 2005 with the flood of 2005 exceeding Q_{10} in the Homathko River. It is assumed here that minor floods affected channels in this study region during these years, where relatively small amounts of bed material sediments were mobilized and channel disturbance was minimal.

Table 9. Discharge magnitude by return period for select Water Survey of Canada gauging stations near the study regions. Records for 2006 were not available for analysis.

Station				Discharge magnitude by return period					
Name	Number	Area (km ²)	Period	(m ³ /s)					
				Q _{2.33}	Q ₅	Q ₁₀	Q ₂₀	Q ₅₀	Q ₁₀₀
Forfar, O'Ne-el, and Thautil study regions:									
North Beach	08JB013	< 20	1998-2004	0.56	0.78	0.92	1.1	1.3	1.5
Van Tine	08JA014	153	1975-2005	9.0	13	16	19	23	25
Two Mile	08EE025	20	1983-2005	0.45	0.64	0.80	1.0	1.1	1.3
Simpson	08EE012	13	1969-2005	2.6	3.3	3.9	4.4	5.2	5.7
Goathorn	08EE008	132	1961-2005	14	18	20	22	27	30
Twain	08EC014	< 15	1975-2005	1.4	1.8	2.1	2.4	2.8	3.1
Chuchinka	07EE009	399	1976-2005	46	58	67	76	87	98
Precipice, Homarko, and Kappan study regions:									
Hamathko	08GD008	500	1968-2005	10	12	14	16	19	21
Lingfield	08MA006	98	1975-2005	8.4	11	12	14	17	18

Table 10. Years in which a reference discharge was exceeded for gauging stations listed in Table 8 during the period of study (1998 or 1999 to 2005). Note that there were no flood events on record during this period that exceeded Q_{50} .

Station Name	Years exceeded by reference discharge				
	$Q_{2.33}$	Q_5	Q_{10}	Q_{20}	Q_{50}
<i>Forfar, O'Ne-el, and Thautil study regions:</i>					
North Beach	-	2003	2002	-	-
Van Tine	2002	-	-	-	-
Two Mile	1999, 2000, 2002	-	2004	-	-
Simpson	-	-	2002	-	-
Goathorn	1999	-	2002	-	-
Twain	2005	2004	2002	-	-
Chuchinka	2000, 2002, 2003	-	1999	-	-
<i>Precipice, Homarko, and Kappan study regions:</i>					
Hamathko	2003	-	-	2005	-
Lingfield	2002, 2003, 2005	-	-	-	-

2.2.2 Landslide

The most recent airphotos taken prior to field work in 1998, 1999 and 2006 were reviewed for the occurrence(s) of landslide and/or large-scale sediment transfer into the channel. Generally, hillslopes were stable over the study period with no visible evidence of recent slide scars apparent on the airphotos. Exceptions occurred in Forfar Creek where a ~280 m cut-bank was being actively eroded (as observed in 1998), and in Gluskie Creek where a small slide reached the channel (as observed in 1998).

2.2.3 Mountain Pine Beetle (MPB) Infestation

The area and intensity of MPB infestation in each watershed is given in Table 11. Data were derived from forest health sketch maps compiled by the BC Ministry of Forests using an overview aerial survey method (see Forest Practices Branch 2006 for details). The maps are compiled annually and describe general trends in MPB infestation across the province. The maps record the presence of red trees representing recent damage visible from an aircraft and not older grey attacks, current or green attacks. Since 2005, polygons have been assigned a tree mortality rating that approximates the percentage of red trees in each polygon. The rating is as follows: < 1% (trace), 1-10% (light), 11-30% (moderate), 30-50% (severe), and >50% (very severe).

3.0 METHODS

Detailed longitudinal profiles were surveyed over extensive channel lengths (approximately 50 bankfull channel widths) to document the morphological condition of each channel. Profiles were surveyed with an automatic level and stadia rod, while distance along the thalweg was measured with a surveyor's hip chain. Thalweg, water surface, bar and bank elevations were measured at a set interval of one bankfull channel width to enable objective analyses of channel characteristics. Other morphological features (e.g., morphologic breaks separating pools and riffles) were measured as supplementary survey points. These were identified in the field by their topographical, sedimentological and hydraulic characteristics (after Keller and Melhorn 1973, Sullivan 1986, Church 1992, Benda et al. 2005). Channel and valley floor widths were measured every fifth channel width.

Surface sediment texture was determined by photographic techniques (see Graham et al. 2005a, Graham et al. 2005b) by averaging results from 5 to 13 individual photographs in channels >5 m in bankfull width (depending on the spatial variability of surface sediments), and by standard Wolman samples of 100 stones in smaller channels.

All woody debris was categorized at each survey interval according to the size (length and mean diameter), position (orientation relative to the banks and vertical placement of a log above the bed or bank), and mode of storage (unconstrained or in a log jam). Riparian surveys were completed along each study reach and consisted of four 3.99 m radius sample plots. Plots were placed approximately 10 bankfull widths apart along the reach and adjacent to the stream banks. Within each plot, tree species, breast height diameter, and the crown height of each tree were determined. Breast height diameter was measured with a DBH tape and used to estimate tree basal area. Crown heights less than 2 to 3 m were measured with a stadia rod, while taller trees were measured with either a survey laser or an inclinometer and chain. Canopy age was determined with an increment bore.

Table 11. MPB infestation in the study basins.

Watershed	Initial attack ^a (yr)	Attack area ^b (basin area %)	Tree mortality range ^c
<i>Thautil study region</i>			
Thautil 1	2001	4.2	Moderate
Thautil 2	2001	37.8	Trace to Moderate
Thautil 3	N/A	0.0	None
<i>O'Ne-el study region</i>			
O'Ne-el	1999	79.9	Trace to Moderate
Bivouac	2004	13.8	Trace to Moderate
Sidney	2001	44.4	Trace to Severe
<i>Forfar study region</i>			
Forfar	2004	19.5	Trace to Moderate
Gluskie	2004	24.5	Trace to Moderate
Van Decar	2001	62.3	Trace to Severe
<i>Hotnarko study region</i>			
Hotnarko	2003	100.0	Low to Severe
Kappan 4	2003	73.1	Trace to Low
Kappan 5	2003	87.1	Trace to Moderate
<i>Precipice study region</i>			
Precipice	2003	52.5	Trace to Low
Nimpo	2003	74.0	Trace to Low
Kappan 3	2003	83.3	Trace to Low
<i>Kappan study region</i>			
Kappan 1	2003	84.2	Trace to Moderate
Natsadalia	2003	96.9	Low to Moderate
Kappan 2	2003	80.8	Trace to Moderate

^a Year in which MPB was first observed in the study watershed after 1998.^b Percent of watershed area infested by MPB between 1999 and 2006.^c Range in tree mortality observed in individual polygons between 1999 and 2006.

4.0 RESULTS AND DISCUSSION

4.1 Riparian forest characteristics

The characteristics of the riparian forest adjacent to the study channels are given in Table 12. The tree canopy was defined by coniferous or deciduous trees ≥ 10 m in height, and included any veteran, dominant or sub-dominant stems. The shrub layer was defined by trees between 1.3 and 10 m in height, and included both saplings and poles. Dominant and sub-dominant tree species in each layer were defined by importance value.

Lodgepole pine is an adaptable tree species that grows in a wide variety of soil and topographic conditions throughout the central interior (Burns and Honkala 1990, Parish and Thomson 1994). However, the species was dominant or sub-dominant in the canopy or shrub layers of only four riparian areas (Kappan 1, Kappan 2, Kappan 5, and Natsadalia). Most canopy layers were dominated by either sub-alpine fir or white spruce with alder and willow common in the shrub layers. Other common species in both the

canopy and shrub layers included black cottonwood, trembling aspen, Douglas-fir, and both water and paper birch.

The distribution of both living and dead lodgepole pine stems in each riparian area is given in Table 13. Overall, lodgepole pine was absent from all riparian areas investigated in the SBS. Sites in the Forfar and O'Ne-el study regions were located in the SBSwk biogeoclimatic subzone, while sites in the Thautil study region were located in the SBSmc biogeoclimatic subzone. Generally, lodgepole pine represents between 2 to 5% and 11 to 25% cover in these subzones, respectively (Meidinger et al. 1991). However, Meidinger et al. (1991) also suggest that throughout moist subzones of the SBS, riparian areas are typically characterized by the Hybrid spruce—Devil's club site association, while the relatively dry uplands and ridge-tops support the Lodgepole pine—Huckleberry—Cladonia site association. This pattern was observed throughout both the O'Ne-el and Forfar study regions, both of which were characterized by relatively large channels with well defined and relatively wide, moist riparian areas. The riparian forests were generally comprised of white spruce and sub-alpine fir with abundant Devil's club in the understory.

In contrast, lodgepole pine was found in most riparian areas of the SBPS zone. Sites in the Kappan, Hotnarko and Precipice study regions were all located in the SBPSxc biogeoclimatic subzone. Lodgepole pine generally comprises 11 to 25% cover of these forests (Steen and Demarchi 1991). Generally, the White spruce—Horsetail—Glow moss site association is common in riparian areas of the SBPS zone and supports occasional lodgepole pine in mature stands, but is also an occasional or dominant tree species in other common site associations throughout the zone (Steen and Demarchi 1991). Approximately two-thirds of lodgepole pine stems in both the canopy and shrub layers in this zone were dead, although the variability amongst sites was relatively high.

Table 12. Riparian forest characteristics adjacent to the study channels.

Site	Layer	Species		SPH (N/ha)	Basal area (m ² /ha)	Volume (m ³ /ha)	Age (yr.)
		Dominant	Subdominant				
Thautil 1 1998	Canopy	Black cottonwood	Alder	400	41.6	400	83
	Shrub	Alder	White spruce	2750	4.1	36.7	24
Thautil 1 2006	Canopy	Black cottonwood	White spruce	450	39.7	356	81
	Shrub	Alder	Willow	3600	7.4	14.4	14
Thautil 2	Canopy	White Spruce	Sub-alpine fir	500	80.2	873	89
	Shrub	White Spruce	Alder	1000	2.4	4.18	10
Thautil 3	Canopy	Sub-alpine fir	White Spruce	750	55.7	410	168
	Shrub	Alder	White Spruce	2200	5.0	9.24	12
O'Ne-el 1999	Canopy	Sub-alpine fir	-	250	17.2	161	129
	Shrub	Alder	Willow	4100	39.8	225	7
O'Ne-el 2006	Canopy	White Spruce	Alder	150	3.9	18.1	129
	Shrub	Alder	Willow	1600	2.9	5.84	8
Bivouac	Canopy	Alder	White Spruce	800	18.4	105	64
	Shrub	Alder	White Spruce	3000	4.5	8.59	13
Sidney	Canopy	Sub-alpine fir	White Spruce	500	14.8	87.9	112
	Shrub	Sub-alpine fir	Alder	2050	8.2	14.6	13
Forfar 1998	Canopy	Sub-alpine fir	White Spruce	350	42.4	451	110
	Shrub	Alder	Sub-alpine fir	1600	6.1	28.5	24
Forfar 2006	Canopy	Alder	-	150	2.9	11.8	38
	Shrub	Alder	Black cottonwood	2500	2.6	6.1	8
Gluskie	Canopy	White Spruce	-	200	19.7	232	114
	Shrub	White Spruce	Alder	3700	4.8	7.98	8
Van Decar	Canopy	Sub-alpine fir	Alder	150	14.0	209.9	58
	Shrub	Alder	Willow	1850	3.5	7.63	8
Hotnarko 1999	Canopy	Water birch	Sub-alpine fir	1300	57.0	377.9	81
	Shrub	Water birch	Sub-alpine fir	2200	6.6	12.5	32
Hotnarko 2006	Canopy	Sub-alpine fir	-	1050	28.2	147	69
	Shrub	Sub-alpine fir	Alder	1700	5.0	10.2	26
Kappan 4	Canopy	Sub-alpine fir	-	2550	39.2	218	63
	Shrub	Sub-alpine fir	Alder	7550	15.5	33.7	34
Kappan 5	Canopy	Sub-alpine fir	Lodgepole pine	1500	42.4	275.7	59
	Shrub	Alder	Lodgepole pine	750	2.7	6.38	9
Precipice 1999	Canopy	Paper birch	Douglas-fir	1150	28.5	159.5	103
	Shrub	Sub-alpine fir	Douglas-fir	2700	6.2	18.96	65
Precipice 2006	Canopy	White Spruce	Sub-alpine fir	600	30.7	223.9	118
	Shrub	White Spruce	Alder	2650	13.6	29.9	25
Nimpo	Canopy	Sub-alpine fir	Alder	550	31.9	273.3	184
	Shrub	Sub-alpine fir	Alder	2000	2.6	4.95	22
Kappan 3	Canopy	Sub-alpine fir	-	550	39.3	313.7	159
	Shrub	Sub-alpine fir	Alder	2100	4.1	7.13	9
Kappan 1 1999	Canopy	Lodgepole pine	Water birch	480	28.5	159.5	54
	Shrub	Alder	Lodgepole pine	240	2.0	5.6	14
Kappan 1 2006	Canopy	Sub-alpine fir	-	50	2.4	8.6	51
	Shrub	Willow	Alder	650	0.31	0.37	7
Natsadalia	Canopy	Sub-apline fir	Lodgepole pine	1050	87.3	790.9	150
	Shrub	Alder	Sub-apline fir	1400	2.9	7.7	13
Kappan 2	Canopy	Lodgepole pine	-	2650	53.7	335.5	71
	Shrub	Lodgepole pine	Trembling aspen	1050	5.7	20.1	7

4.2 Riparian Woody Debris Recruitment

The tree fall model developed by Van Sickle and Gregory (1990) was used here to estimate the volume of riparian trees transferred to a channel in the SBPS zone (this exercise was not completed in the SBS zone since there were no lodgepole pine trees in the riparian areas sampled—see previous section). The model requires field data including channel width, stem density, breast height diameter, and height for all trees by species in the riparian area. The average volume (V) of a single tree entering a channel following mortality was estimated by

$$E(V) = \int_{a_s}^{180^\circ - a_s} V(a) f(a) da \quad [\text{Eq. 3}]$$

after Van Sickle and Gregory (1990), where $V(a)$ is the log volume entering a channel at angle a , and $f(a)$ is the probability of a log falling at angle a . A random fall probability was assumed for each standing tree, although it is possible that a preferred fall direction exists in many riparian areas (e.g., trees may be more likely to fall towards the channel, especially if the riparian area is relatively steep). A random fall probability likely represents the minimum input to the channel. Eq. [3] was integrated over the limits of $180^\circ - a_s$ to a_s , representing an arc defined by the tree crown as it intersects the channel banks at angle a_s and then again at $180^\circ - a_s$. Eq. [3] was summed over all tree species, tree heights, and distance classes from the stream bank. The model accounts for tree height, log taper (it was assumed each log could be described by a cone), and distance from the stream bank. Complete details are given in Van Sickle and Gregory (1990). In small streams, wood is often suspended above the channel banks due to relatively narrow channel widths (relative to tree heights) and hillslope confinement, and direct input to the channel may not occur until a log is either broken or fragmented (Nakamura and Swanson 1994). The model accounts for above-bank storage but not breakage of the stem on or after impact with the ground, likely underestimating actual input to the channel boundary.

Table 13. Distribution of lodgepole in the riparian forest adjacent to the study channels (as surveyed in 2006). Red and grey trees were recorded as "dead" (current or green attacks were not included in this total).

Site	Dead lodgepole pine stems						All lodgepole pine stems					
	Canopy			Shrub			Canopy			Shrub		
	SPH (N/ha)	Basal area (m ² /ha)	Volume (m ³ /ha)	SPH (N/ha)	Basal area (m ² /ha)	Volume (m ³ /ha)	SPH (N/ha)	Basal area (m ² /ha)	Volume (m ³ /ha)	SPH (N/ha)	Basal area (m ² /ha)	Volume (m ³ /ha)
Thautil 1	-	-	-	-	-	-	-	-	-	-	-	-
Thautil 2	-	-	-	-	-	-	-	-	-	-	-	-
Thautil 3	-	-	-	-	-	-	-	-	-	-	-	-
O'Ne-el	-	-	-	-	-	-	-	-	-	-	-	-
Bivouac	-	-	-	-	-	-	-	-	-	-	-	-
Sidney	-	-	-	-	-	-	-	-	-	-	-	-
Forfar	-	-	-	-	-	-	-	-	-	-	-	-
Gluskie	-	-	-	-	-	-	-	-	-	-	-	-
Van Decar	-	-	-	-	-	-	-	-	-	-	-	-
Hotnarko	-	-	-	-	-	-	-	-	-	-	-	-
Kappan 4	-	-	-	-	-	-	-	-	-	-	-	-
Kappan 5	-	-	-	100	0.28	0.35	550	12.0	69.6	150	0.90	1.9
Precipice	200	9.4	66.8	200	9.4	66.8	200	9.4	66.8	200	9.4	66.8
Nimpo	150	15.9	124	50	3.7	8.05	150	15.9	124	50	3.7	8.05
Kappan 3	50	6.8	49.2	-	-	-	50	6.8	49.3	-	-	-
Kappan 1	450	28.3	133	50	2.2	6.2	450	28.3	133	50	2.2	6.2
Natsadalia	50	2.4	17.3	-	-	-	100	8.5	80.3	-	-	-
Kappan 2	200	0.70	2.38	2750	10.0	21.4	2900	55.7	342	3400	14.0	31.3

The total volume of trees (V_{Tm}) entering a channel following mortality was estimated by

$$E(V_{T_m}) = \sum D_s \Delta z_k L_r P_F E(V) \quad [\text{Eq. 4}]$$

after Van Sickle and Gregory (1990), where D_s is the stand density, z_k represents the distance of a tree from the stream banks, L_r is reach length, and P_F is the probability of a tree falling during t_i to t_{i+1} . The equation is summed over all tree species, tree heights, and distance classes from the stream bank (see Van Sickle and Gregory (1990) for additional details). It was assumed here that P_F could be estimated by the inverse of the average age at which mortality occurs for a given tree species (given in Table 14). It was further assumed that P_F includes mortality by wind, fire, insect and competition from other stems. However, this estimate does not account for the period a tree may remain standing as a snag following death (standing time). In the Engelmann Spruce—Sub-alpine Fir biogeoclimatic zone (Coupe et al. 1991), the maximum age of most Engelmann spruce snags may approach 20 years (DeLong et al. 2005), while most sub-alpine fir snags may approach 60 to 70 years (Huggard 1999, DeLong et al. 2005). Generally, the size of the snag is more important than the species, as larger snags are more resistant to decay and can often stand for longer periods (Morrison and Raphael 1993). For simplicity and to facilitate modeling in this report, all snags with the exception of lodgepole pine snags were assumed to stand for an average of 40 years, at most, following death (i.e., 40 years were added to the ages of mortality for all species given in Table 14). Existing snags surveyed in the riparian canopy were assumed to have already stood for 20 years and would remain standing for another 20 years. Lewis and Hartley (2005) review previous studies of the standing time of lodgepole pine trees following mortality from MPB in British Columbia and other regions of Western North America, and suggest that in the SBSmc and wk biogeoclimatic subzones, 90% of lodgepole pine stems will have fallen within 15 years of death. They also suggest that wet sites and stands with a high mortality rate (and therefore higher soil moisture) will have a higher fall rate due to increased rates of basal decay. In the relatively wet riparian areas in the SBPS studied here, it is assumed most lodgepole pine snags will stand for 15 years before falling.

Table 14. Maximum tree age used to estimate the probability of tree mortality in a given year.

Common name	Scientific name	Maximum age (yr)	Source
Lodgepole pine	<i>Pinus contorta</i> var. <i>latifolia</i>	500	Urban et al. (1993)
Sub-alpine fir	<i>Abies lasiocarpa</i>	300	Urban et al. (1993)
White spruce	<i>Picea glauca</i>	400	Cumming and Burton (1996)
Alder	<i>Alnus</i> sp.	100	Burns and Honkala (1990)
Willow	<i>Salix</i> sp.	100	Estimated
Black cottonwood	<i>Populus balsamifera</i> ssp. <i>trichocarpa</i>	250	Urban et al. (1993)
Trembling aspen	<i>Populus tremuloides</i>	200	Burns and Honkala (1990)
Interior Douglas-fir	<i>Acer glabrum</i>	700	Cumming and Burton (1996)
Paper birch	<i>Betula papyrifera</i>	140	Bonan (1989)
Water birch	<i>Betula occidentalis</i>	140	Estimated

Recruitment from bank erosion was estimated by

$$E(V_{r_b}) = \sum D_s E L_r P_r E(V) \quad [\text{Eq. 5}]$$

after Van Sickle and Gregory (1990), where E is the linear rate of bank retreat per year (assumed here as 0.005 m yr^{-1} ; actual rates are poorly documented). P_r was set at 1.0 as each log undermined by a collapsing bank was assumed to enter the channel. Eq. [5] was summed over all tree species, tree heights, and distance classes from the stream bank.

Four scenarios were considered. First, pre-MPB infestation rates of woody debris input were approximated by treating all lodgepole pine snags as live stems. These likely underestimate actual input rates, as there may have been a snag(s) in a given stand unrelated to MPB-related mortality. Second, current rates of woody debris transfer were estimated directly from the field data. Third, in the cases where there remained a living lodgepole pine stem(s) in a given riparian area at the time of field survey, the model was run by treating all living lodgepole pine stems as snags. This approximates a worst-case scenario (peak input rates) that assumes an eventual 100% mortality rate in each riparian area. Shore et al. (2006) suggests lodgepole pine mortality may approach 100% in mature stands growing in high climatic hazard areas, but at the landscape level mortality rates in a stand may more typically range from 25 to 50%. Fourth, the model was run with no lodgepole pine stems (living trees or snags) to approximate post-MPB conditions once all trees are infected and have fallen to the ground. With the exception of lodgepole pine, each scenario assumes the composition of the forest remains the same as sampled during the field survey (i.e., the model does not include a growth and yield component).

The results are given in Table 15. Annual pre-infestation mortality rates of input ranged from 0.0782 to $33.8 \times 10^{-5} \text{ m}^3/\text{m}^2$. The highest rate was in Natsadailia Creek, given a relatively high stem density of large diameter trees. Generally, differences in the input rate were due to stem density and species composition (relatively frequent, large and/or short-lived trees contribute to a higher rate). Channel width is also an important factor in the input rate, with relatively wide channels receiving more wood than narrow channels (although this caused only minor differences in these results given selection of similar channels). Current levels of MPB infestation have increased the rate of wood input by mortality by a factor of about 2.2, with projected rates of peak-MPB infestation expected to increase by a factor of about 3.7 over pre-infestation rates (averaged over all sites in the SBPS zone). Sites most affected are dominated by lodgepole pine with relatively few other species in the canopy (see Tables 12 and 13). Average annual peak-MPB infestation input rates range from 2.45 to $47.1 \times 10^{-5} \text{ m}^3/\text{m}^2$ and are expected to persist for the standing time of lodgepole pine snags. Once all lodgepole pine has fallen, post-MPB rates of input drop to about 0.78 of pre-infestation rates, and range from 0.00256 to $32.8 \times 10^{-5} \text{ m}^3/\text{m}^2$.

Rates of wood transferred to the channel through bank erosion were generally less than those associated with mortality and ranged from 0.947 to $9.04 \times 10^{-5} \text{ m}^3/\text{m}^2$ in each of the pre-MPB, current, and peak-MPB infestation scenarios (Table 15). Rates do not vary within a site during these periods since wood recruitment from bank erosion does not

depend on the time a tree may stand as a live stem and/or as a snag. Rather, rates depend on the rate of bank erosion, channel width, and the volume of wood standing in the riparian area. Post-MPB rates of wood transfer drop from between 0.00208 to 7.94×10^{-5} m^3/m^2 once all lodgepole pine snags have fallen.

Table 15. The rate of woody debris input to each channel in the SBPS zone. Rates were not calculated for channels in the SBS zone since there was no lodgepole pine in the riparian area in any of the sites sampled. Data have been standardized by reach length and channel width to allow comparison among sites, and represent the average annual volume of wood transferred to 1 m² of channel. Chronic woody debris input is about 1.3 times greater than the acute input rate.

Site	Mode of wood input (x 10 ⁻⁵ m ³ /m ² /yr)												
	Chronic												
	Mortality				Bank erosion				Total				Acute ^c
	Pre-MPB ^a	Current ^b	Peak ^c	Post-MPB ^d	Pre-MPB	Current	Peak	Post-MPB	Pre-MPB	Current	Peak	Post-MPB	
Hotnarko	4.69	4.69	4.69	4.69	1.84	1.84	1.84	1.84	6.53	6.53	6.53	6.53	6.63
Kappan 4	2.45	2.45	2.45	2.45	2.18	2.18	2.18	2.18	4.63	4.61	4.63	4.63	5.65
Kappan 5	3.66	3.69	9.63	3.18	2.79	2.79	2.79	2.05	6.46	6.48	12.4	5.23	10.2
Precipice	6.46	11.5	11.5	6.06	2.88	2.88	2.88	2.37	9.34	14.3	14.3	8.43	11.0
Nimpo	16.3	30.7	30.7	15.1	4.16	4.16	4.16	2.81	20.4	34.9	34.9	17.9	19.5
Kappan 3	5.23	9.30	9.30	4.90	3.16	3.16	3.16	2.75	11.6	15.6	15.6	10.4	13.7
Kappan 1	0.782	6.55	6.55	0.320	0.947	0.947	0.947	0.223	1.73	7.5	7.50	0.542	3.10
Natsadalia	33.8	46.2	47.1	32.8	9.04	9.04	9.04	7.94	42.9	55.4	56.2	40.7	37.2
Kappan 2	2.36	4.08	31.8	0.00256	3.69	3.69	3.69	0.00208	6.05	7.77	35.5	0.00464	12.7

^a Rate of input assuming all lodgepole pine in the sample was alive (i.e., snags were considered as live stems) to approximate pre-MPB infestation conditions

^b Rate of input at the time of field survey

^c Rate of input assuming all lodgepole pine in the sample was dead (i.e., living trees were considered as snags) to approximate peak infestation conditions (assuming 100% mortality of lodgepole pine trees)

^d Rate of input with all lodgepole pine stems removed from the sample to approximate post-MPB conditions once all lodgepole pine snags have fallen

^e Estimate of the average volume of wood transferred to the channel during a stand-replacing event standardized by an average return period of 100 years

4.3 Woody Debris Budget

Recruitment rates of woody debris from the riparian area were related to the storage of woody debris in the channel by constructing a woody debris (see for review, Benda et al. 2002, Benda et al. 2003, Benda and Sias 2003). The budget is given by

$$I + \Delta S = O \quad [6]$$

where I is the rate of wood input to a channel (m^3/yr), ΔS is the change in wood storage (m^3/yr), and O is the output of wood from a channel (m^3/yr). General sources of woody debris to small streams are summarized by Hassan et al. (2005). In this report, I is restricted to inputs from mortality (I_m) and bank erosion (I_b) as calculated above. Other sources such as landslide and transport from an upstream reach (amongst others) were considered negligible in this geomorphic setting and are not included in the budget presented here. The output terms associated with O primarily consist of orogenic decay (O_d) and abrasion (O_a). Loss of wood through transport to downstream reaches was considered negligible in the small channels surveyed in this report. The budget can then be expressed as

$$I_m + I_b + \Delta S = O_d + O_a \quad [7]$$

The output terms expressed in Eq. [7] are difficult to measure directly. As an approximation, the sum of O_d and O_a was calculated with an exponential decay model

$$V_t = V_0 e^{-kt} \quad [8]$$

where V_t is the volume of woody debris (m^3) at time t (yr) and V_0 is the volume of woody debris at initial conditions (m^3). The decay constant k was taken as the mean weighted age of woody debris stored in the channel

$$k = \sum \frac{1}{a_i p_i} \quad [9]$$

where a is the age (yr) and p is the proportion of wood stored in the i^{th} log jam in the reach (Murphy and Koski 1989). The output of woody debris can then be estimated by

$$O = \frac{V_0 - V_t}{t} \quad [10]$$

The budget can then be written as

$$I_m + I_b + \Delta S = \frac{V_0 - V_t}{t} \quad [11]$$

The ΔS of woody debris was then calculated for each scenario following MPB infestation by Eq. [11]. V_t at the end of each period was taken as V_o at the start of the following period. The length of the current period (t_c) was set to 10 years, equivalent to the average duration of an outbreak in a stand (see Safranyik and Carroll 2006), and starting from the year of initial attack in a watershed (see Table 11). The length of the peak period (t_p) was set at 15 years and assumed equivalent to the average time for lodgepole pine snags to fall (as described above). Shore et al. (2006) suggest that following infestation, trees that remain in a stand may eventually replace the volume of wood lost through the mortality of lodgepole pine by about the time of one harvest rotation. As a conservative estimate, the length of the post-MPB period (t_{pt}) was limited to 50 years, after which growth of successional trees species that replace dead lodgepole pine may bias the estimate of riparian wood input. This enables the woody debris budget in a channel over a total period of 75 years following the initial infestation of MPB in the adjacent riparian area. This also assumes the absence of a major stand-replacing disturbance such as fire or salvage logging. The minimum age of the riparian canopies surveyed in 2006 averaged 103 years and ranged from 51 to 184 years (Table 12). Throughout the SBPS zone, stand initiating events may occur at a mean return interval of 100 years (BC Ministry of Forests and BC Ministry of Environment 1995) and are often caused by combinations of fire and MPB infestation (Wong et al. 2003).

An average k value of 0.038 was calculated from the field data. Given the properties of an exponential function, this suggests the average residence time of woody debris in small channels in the SBPS is 26 years. However, relatively small pieces of debris are likely removed from the channel after a decade while larger logs may persist for a century. The change in woody debris storage was then calculated for each year given in periods described above, given the expected pattern of input following MPB infestation. The calculation was repeated for uninfested conditions assuming all lodgepole pines were alive when field work occurred. The results of the woody debris budget are given in Figure 2. Generally, the change in stored woody debris volume induced by MPB infestation is relatively minor, but will persist until about 2050. The maximum increase in storage occurs between 2026 and 2029 (near the end of the t_p period). The largest increase occurs in Natsadalia and Nimpo creeks where woody debris storage increases by 2.15 and $2.32 \times 10^{-3} \text{ m}^3/\text{m}^2$, respectively. The remaining sites with lodgepole pine in the riparian area increase storage volumes by an average of $7.6 \times 10^{-4} \text{ m}^3/\text{m}^2$. Overall, these increases are considered minor given that they represent on average about 10% of the acute rate of input during a stand-replacing event.

Two general conditions of wood storage are apparent in Figure 2. The first is where existing storage of woody debris is less than the volume from an acute input, while the second is where the opposite conditions prevail. These are termed here as woody debris “depleted” and “packed” channels, respectively. The occurrence of these conditions vary in both time and space (study regions defined in previous sections), likely reflecting the local disturbance history in a watershed (in the SPBS, this is likely a combination of fire and MPB infestation). For example, the average age of the riparian areas (see Table 12) of depleted and packed channels (at the time of the field survey) are 125 and 83 respectively, while the average return period for a stand-replacing event in this region is

100 years. This suggests that the woody debris budget in these channels is dominated by stand-replacing events (typically fire) that transfers large volumes of wood to a channel over a relatively short period (approximately two to seven times the existing storage volume in depleted channels). This transforms the channel to packed conditions where the channel gradually removes wood through decay and abrasion until storage volumes become relatively low and depleted conditions prevail once again. This pattern repeats itself once the riparian canopy is developed and then subsequently destroyed again. For example, sites such as Hotnarko, Precipice, and Kappan 4 are both packed and on the relatively steep portion of the exponential curve (in 2006), suggesting a relatively recent disturbance has transferred large volumes of woody debris to the channel in each watershed. In contrast, Nimpo, Kappan 5, and Kappan 2 creeks are on the relatively flat portion of the curve and have depleted conditions, suggesting a lack of recent disturbance events in each watershed. Although the MPB infestation is now considered at epidemic levels across the landscape, riparian areas surveyed in this report support relatively small volumes of lodgepole pine (if any). In comparison to the volume of wood transferred to the channel during a stand-replacing event, wood transfer to the channel induced by MPB infestation in the next 25 years is likely to be relatively small and within the range of typical conditions throughout the region.

4.4 Jam frequency

Although results of the woody debris budget suggested that woody debris dynamics have been relatively unaffected by infestation of MPB in riparian areas, the frequency of log jams in the six control watersheds was compared before and after the infestation to confirm the results. The characteristics of a jam (e.g., Hogan and Bird 1998) were not considered here given the relatively small number of jams in the sample. The results are given in Table 16. Overall, there has been no change in the number of log jams following infestation of MPB. Two additional jams were created in Forfar Creek, as an existing jam broke apart, while a jam originally surveyed in 1999 in Kappan 1 Creek was not identified in 2006 (likely decayed or broken apart).

Table 16. Chi-square analysis of the frequency of log jams in the six control watersheds (expected values are given in parentheses). Kappan 1 and Hotnarko creeks were combined to increase the number of observations in the category.

	Watershed					Total
	Forfar	O'Ne-el	Thautil	Kappan 1 & Hotnarko	Precipice	
Pre-MPB	13 (13.9)	8 (7.9)	10 (9.9)	8 (7.4)	13 (12.9)	52
Current	15 (14.1)	8 (8.1)	10 (10.1)	7 (7.6)	13 (13.1)	53
Total	28	16	20	15	26	105

$\chi^2_{0.05, 4} = 9.488$, $\chi^2 = 0.200$, accept H_0

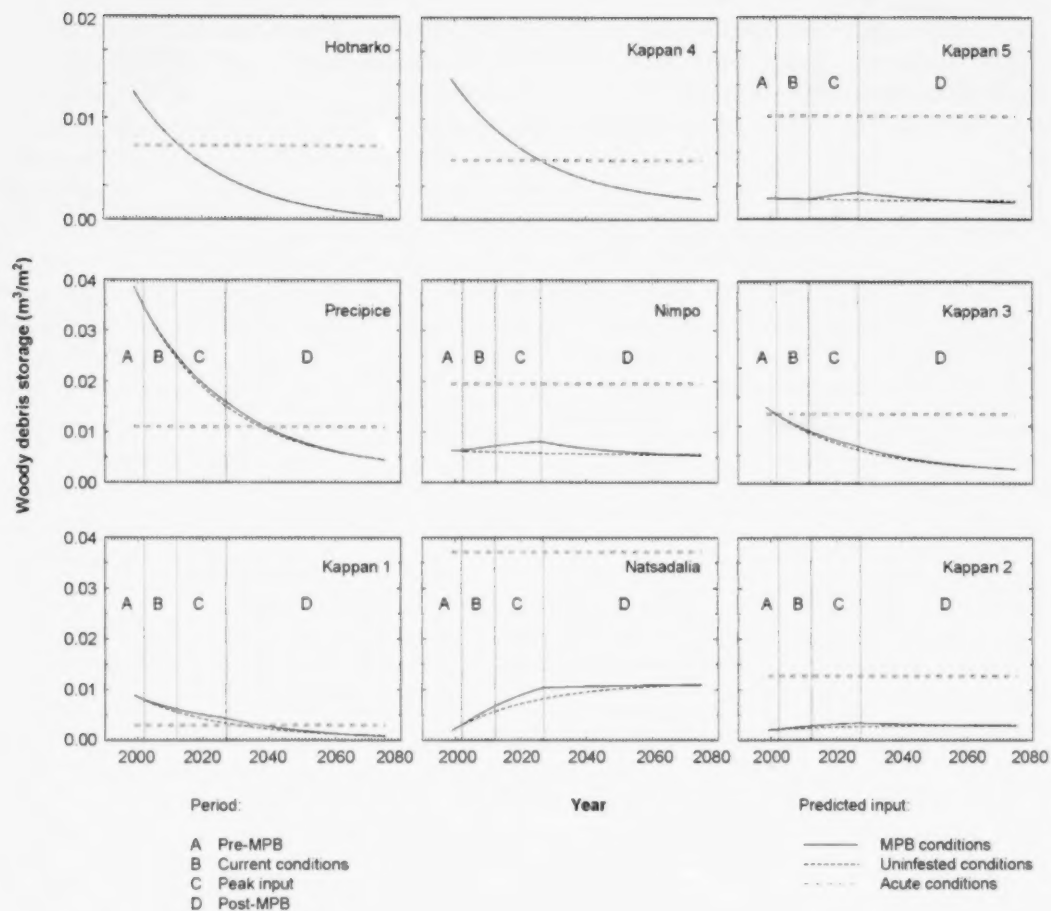


Figure 2. Storage volumes of woody debris following MPB infestation in streams of the SBPS.

The frequency of log jams across the study regions and biogeoclimatic zone was assessed by two factor ANOVA (Table 17). The results suggests there was a significant difference in frequencies between biogeoclimatic zone, but not among study regions (or the interaction between biogeoclimatic zone and study region). Log jam frequencies averaged 0.12 and 0.17 jams per bankfull width along the channel in the SBPS and the SBS zones, respectively. This suggests that characteristics of the riparian area (tree species, density, and volume) are a more important determinant of log jam distribution than the watershed or channel types considered in this report.

Table 17. Summary of the two factor ANOVA used to test for differences in log jam frequencies between biogeoclimatic zones and study regions (and the interaction between both groups). The arcsine transformation was used to normalize the data.

Source of variation	SS	DF	MS	F ratio	F _{0.05(1)}
Total	59383	17			
Cells					
Biogeoclimatic zone (A)	18354	1	18354	6.63	4.75
Study region (B)	1075	2	5377	0.19	3.89
A x B	6715	2	3357	1.21	3.89
Within cells (error)	33239	12	12		

5.0 CONCLUSIONS

Woody debris is a dominant control of channel morphology in small streams throughout British Columbia. In the absence of mass wasting, woody debris inputs to small channels in stable, low gradient watersheds are dominated by riparian sources. Although the MPB infestation is currently at an epidemic level, lodgepole pine was most often absent from the 18 riparian areas studied in this report. Most canopy layers were dominated by either sub-alpine fire or white spruce with alder and willow common in the shrub layers. Lodgepole pine was only identified in seven riparian areas in the SBPS zone (but was the dominant species in Kappan 1 and Kappan 2 creeks). Field observations suggested that beyond the width of the riparian area, lodgepole pine were often found growing in dense, even-aged stands with evidence of forest fire (especially in the SBPS zone). The relatively cool, moist microclimate of the riparian area may sufficiently reduce the reoccurrence and intensity of fire in these stands and limit the distribution of lodgepole pine in riparian areas.

In riparian areas that supported lodgepole pine, about two-thirds of the stems in both the canopy and shrub layers were dead. Assuming a worst-case scenario with 100% mortality, the input rates of woody debris may increase by a factor of about 3.7 over pre-infestation rates, ranging from 2.45 to 47.1 $\times 10^{-5}$ m³/m²/yr. This increase is expected to persist for 15 years following the end of the MPB outbreak (roughly the standing time of lodgepole pine snags). As a result, the net storage of woody debris expected to increase by at least 7.6 $\times 10^{-4}$ m³/m² and by as much as 2.32 $\times 10^{-3}$ m³/m² in some streams by the year 2026 to 2029. Higher storage volumes will persist until about 2050 as wood

transferred to the channel from MPB related sources eventually decays (the average residence time of woody debris in small streams of the SBPS was 26 years).

The increase in woody debris storage resulting from the mortality of MPB-infested lodgepole pine forests is relatively minor compared to the undisturbed range of woody debris dynamics. The woody debris budget in the small channels of the SBPS studied here is dominated by stand-replacing events (typically fire with a 100-year return period) that transfers large volumes of wood to a channel over a relatively short period. On average, the predicted input of woody debris transferred following MPB infestation is expected to be about 10% of that derived from a stand-replacing event. Over the short term, there has been no change in the number of log jams in any of the channels in either the SBPS or the SBS zones (between 1998 or 1999 and 2006). Over the next several decades, these relatively small changes in wood storage volumes may induce some localized channel instability, but is not expected to alter channel morphology at the landscape scale. Management of riparian areas for the supply of woody debris to small channels in areas infested by MPB may be effectively undertaken using existing regulations and guidelines of the Forest and Range Practices Act, and evaluations undertaken as part of the Forest and Range Evaluation Program, currently accepted in the Province of British Columbia. Additional research should focus on quantification of the distribution of lodgepole pine in riparian areas of the SBPS and SBS and the influence of channel type, size, and watershed position.

6.0 ACKNOWLEDGEMENTS

This project was funded by the Government of Canada through the Mountain Pine Beetle Initiative, a Program administered by Natural Resources Canada, Canadian Forest Service. Publication does not necessarily signify that the contents of this report reflect the views or policies of Natural Resources Canada – Canadian Forest Service. Forest Renewal BC and the Fish-Forestry Interaction Project (FFIP II) provided additional funding to Dan Hogan for this project.

7.0 LITERATURE CITED

- Agriculture and Agri-Food Canada. 1996. Soil Landscapes of Canada, Version 2.2 [map]. 1:1,000,000. National Soil Database, Canadian Soil Information System. Agriculture and Agri-Food Canada, Ottawa.
- BC Geological Survey. 1997. Mineral Potential Project 1992-96 [map]. BC Ministry of Energy and Mines, Victoria, BC.
- BC Ministry of Forests. 2003. Biogeoclimatic Subzone Variant Mapping, V5 [map]. BC Ministry of Forests, Victoria, BC.
- BC Ministry of Forests and BC Ministry of Environment. 1995. Biodiversity Guidebook. Forest Practices Code of British Columbia, Victoria, BC.
- BC Ministry of Forests and Range. 2005. 2005 Summary of forest health conditions in British Columbia. Pest Management Report Number 15, Forest Practices Branch, BC Ministry of Forests and Range, Victoria, BC.

- Benda, L.; Hassan, M.; Church, M.; May, C.L. 2005. Geomorphology of steep-land headwaters: The transition from hillslopes to channels. *Journal of the American Water Resources Association*, 41:835-851.
- Benda, L.; Miller, D.; Sias, J.; Martin, D.; Bilby, R.E.; Veldhuisen, C.; Dunne, T. 2003. Wood recruitment processes and wood budgeting. *In* Gregory, S. V., K. L. Boyer and A. M. Gurnell (editors). *The ecology and management of wood in World Rivers*. American Fisheries Society, Bethesda, Maryland, pp. 49-74.
- Benda, L. E.; Bigelow, P.; Worsley, T.M. 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, USA. *Canadian Journal of Forest Research*, 32:1460-1477.
- Benda, L. E.; Sias, J.C. 2003. A quantitative framework for evaluating the mass balance of in-stream organic debris. *Forest Ecology and Management*, 172:1-16.
- Bilby, R. E.; Bisson, P.A. 1998. Function and distribution of large woody debris. *In* Naiman, R. J. and R. E. Bilby (editors). *River ecology and management*. Springer, New York, pp. 324-346.
- Bilby, R. E.; Ward, J.W. 1989. Changes in Characteristics and Function of Woody Debris with Increasing Size of Streams in Western Washington. *Transactions of the American Fisheries Society*, 118:368-378.
- Bisson, P. A.; Bilby, R.E.; Bryant, M.D.; Dollof, C.A.; Grette, G.B.; House, R.A.; Murphy, M.L.; Koski, K.V.; Sedell, J.R. 1987. Large woody debris in forest streams in the Pacific Northwest: Past, present, and future. *In* Salo, E. O. and T. W. Cundy (editors). *Stream Management: Forestry and Fisheries Interaction*. Institute of Forest Resources, University of Washington, Seattle, Washington, pp. 143-190.
- Bonan, G. B. 1989. Environmental factors and ecological processes controlling vegetation patterns in boreal forests. *Landscape Ecology*, 3:111-130.
- Burns, R. M.; Honkala, B.H. 1990. *Silvics of North America: I Conifers: 2. Hardwoods*, Vol. 2 edition. U.S. Department of Agriculture, Forest Service, Washington, D.C.
- Cheong, A. L. 1992. Quantifying drainage basin comparisons within a knowledge-based system framework. Unpublished M.Sc. thesis. Department of Geography, University of British Columbia, Vancouver, B.C.
- Cheong, A. L. 1993. British Columbia Watershed Classification Project (Draft). Unpublished report submitted to BC Ministry of Environment and BC Ministry of Forests, Victoria, BC.
- Church, M. 1992. Channel morphology and typology. *In* Calow, P. and G. E. Petts (editors). *The Rivers Handbook: Hydrological and Ecological Principles*. Blackwell, Oxford, pp. 126-143.
- Church, M. 1997. Hydrological Zones for British Columbia [map]. 1:7,000,000. Regionalized Hydrological Estimates for British Columbia: First Approximation of Scale Effect. Resources Inventory and Data Management Branch, British Columbia Ministry of Environment, Lands and Parks, Victoria B.C.
- Coupe, R.; Stewart, A.C.; Wikeem, B.M. 1991. Englemann Spruce—Subalpine Fir Zone. *In* Meidinger, D. and J. Pojar (editors). *Ecosystems of British Columbia*. Research Branch, BC Ministry of Forests, Victoria, BC, pp. 223-236.
- Cumming, S. G.; Burton, P.J. 1996. Phenology-mediated effects of climatic change on some simulated British Columbia forests. *Climatic Change*, 34:213-222.

- Delong, S. C.; Daniels, L.D.; Heemskerk, B.; Storaunet, K.O. 2005. Temporal development of decaying log habitats in wet spruce-fir stands in east-central British Columbia. *Canadian Journal of Forest Research*, 35:2841-2850.
- Eaton, B.; Church, M.; Ham, D. 2002. Scaling and regionalization of flood flows in British Columbia, Canada. *Hydrological Processes*, 16:3245-3263.
- Eng, M.; Fall, A.; Hughes, J.; Shore, T.L.; Riel, B.; Walton, A.; Hall, P. 2006. Provincial-level projection of the current mountain pine beetle outbreak: Update of the infestation projection based on the 2005 Provincial Aerial Overview of Forest Health and revisions to "the model" (BCMPB.v3). Research Branch, BC Ministry of Forests and Range, Victoria, BC.
- Forest Practices Branch. 2006. Forest Health – Aerial Overview Survey. BC Ministry of Forests and Range, Victoria, BC. www.for.gov.bc.ca/hfp/health/overview/overview.htm, updated April 3, 2006 (accessed March 12, 2007).
- Gordon, A. D. 1981. *Classification: Methods for the Exploratory Analysis of Multivariate Data*. Chapman and Hall, London.
- Graham, D. J.; Reid, I.; Rice, S.P. 2005a. Automated sizing of coarse-grained sediments: Image-processing procedures. *Mathematical Geology*, 37:1-28.
- Graham, D. J.; Rice, S.P.; Reid, I. 2005b. A transferable method for the automated grain sizing of river gravels. *Water Resources Research*, 41.
- Hassan, M. A.; Hogan, D.L.; Bird, S.A.; May, C.L.; Gomi, T.; Campbell, D. 2005. Spatial and temporal dynamics of wood in small streams of the Pacific Northwest. *Journal of the American Water Resources Association*, 41:899-919.
- Hey, R. D. 1979. Flow Resistance in Gravel-bed Rivers. *Journal of the Hydraulics Division*, 105:365-379.
- Hogan, D. L. 1986. Channel morphology of unlogged, logged, and debris torrented streams in the Queen Charlotte Islands. Land Management Report No. 49, BC Ministry of Forests, Victoria, BC.
- Hogan, D. L.; Bird, S.A. 1998. Classification and assessment of small coastal stream channels. In Hogan, D. L., P. J. Tschaplinski and S. C. Chatwin (editors). *Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: Applying 20 Years of Coastal Research to Management Solutions*. Land Management Handbook Number 41. B.C. Ministry of Forests, Research Branch, Victoria, BC, pp. 189-200.
- Hogan, D. L.; Bird, S.A.; Hassan, M.A. 1998a. Spatial and temporal evolution of small coastal gravel-bed streams: the influence of forest management on channel morphology and fish habitat. In Klingeman, P. C., R. L. Beschta, P. D. Komar and J. B. Bradley (editors). *Gravel-Bed Rivers in the Environment*. Water Resources Publications, LLC, Highland Ranch, Colorado, USA, pp. 365-392.
- Hogan, D. L.; Bird, S.A.; Rice, S. 1998b. Stream channel morphology and recovery processes. In *Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: Applying 20 Years of Coastal Research to Management Solutions*. Land Management Handbook Number 41. Hogan, D. L., P. J. Tschaplinski and S. C. Chatwin (editors). BC Ministry of Forests, Research Branch, Victoria, BC, pp.
- Holland, S. S. 1965. Landforms of British Columbia: a physiographic outline. Bulletin 48, British Columbia Department of Mines and Petroleum Resources.

- Huggard, D. J. 1999. Static life-table analysis of fall rates of sub-alpine fir snags. *Ecological Applications*, 9:1009-1016.
- Johnson, S. L.; Swanson, F.J.; Grant, G.E.; Wondzell, S.M. 2000. Riparian forest disturbances by a mountain flood -- the influence of floated wood. *Hydrological Processes*, 14:3031-3050.
- Keller, E. A.; Melhorn, W.N. 1973. Bedforms and fluvial processes in alluvial stream channels: selected observations. *In* Morisawa, M. (editor). *Fluvial Geomorphology*. New York State University Publications in Geomorphology, Binghamton NY, pp. 253-283.
- Keller, E. A.; Swanson, F.J. 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes*, 4:361-380.
- Lewis, K. J.; Hartley, I. 2005. Rate of deterioration, degrade and fall of trees killed by mountain pine beetle: A synthesis of the literature and experimental knowledge. Mountain Pine Beetle Initiative Working Paper 2005-14, Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC.
- Lienkaemper, G. W.; Swanson, F.J. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forest. *Canadian Journal of Forest Research*, 17:150-156.
- Meidinger, D.; Pojar, J.; Harper, W.L. 1991. Sub-Boreal Spruce Zone. *In* Meidinger, D. and J. Pojar (editors). *Ecosystems of British Columbia*. Research Branch, BC Ministry of Forests, Victoria, BC, pp. 209-236.
- Montgomery, D. R.; Abbe, T.B.; Buffington, J.M.; Peterson, N.P.; Schmidt, K.M.; Stock, J.D. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature*, 381:587-588.
- Morrison, M. L.; Raphael, M.G. 1993. Modelling the dynamics of snags. *Ecological Applications*, 3:322-330.
- Murphy, M. L.; Koski, K.V. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. *North American Journal of Fisheries Management*, 9:427-436.
- Nakamura, F.; Swanson, F.J. 1994. Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon. *Canadian Journal of Forest Research*, 24:2395-2403.
- Parish, R.; Thomson, S. 1994. *Tree Book: Learning to Recognize Trees of British Columbia*, 2nd edition. Canadian Forest Service and BC Ministry of Forests, Victoria, BC.
- Rodda, J. C. 1976. Basin studies. *In* Rodda, J. C. (editor). *Facets of Hydrology*. John Wiley and Sons Ltd., New York, pp. 368.
- Safranyik, L.; Carroll, A.L. 2006. The biology and epidemiology of the mountain pine beetle in lodgepole pine forests. *In* Safranyik, L. and W. R. Wilson (editors). *The Mountain Pine Beetle: a Synthesis of Biology, Management, and Impacts on Lodgepole Pine*. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, pp. 3-66.
- Shore, T. L.; Safranyik, L.; Hawkes, B.C. Taylor, S.W. 2006. Effects of the mountain pine beetle on lodgepole pine stand structure and dynamics. *In* The Mountain Pine Beetle: a Synthesis of Biology, Management, and Impacts on Lodgepole Pine. Safranyik, L. and W. R. Wilson (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, pp. 95-114.

- Shore, T. L.; Safranyik, L.; Lemieux, J.P. 2000. Susceptibility of lodgepole pine stands to the mountain pine beetle: Testing of a rating system. *Canadian Journal of Forest Research*, 30:44-49.
- Steen, O.; Demarchi, D.A. 1991. Sub-Boreal Pine—Spruce Zone. *In* Meidinger, D. and J. Pojar (editors). *Ecosystems of British Columbia*. Research Branch, BC Ministry of Forests, Victoria, BC, pp. 195-202.
- Sullivan, K. 1986. Hydraulics and fish habitat in relation to channel morphology. Ph.D. John Hopkins University, Baltimore.
- Urban, D. L.; Harmon, M.E.; Halpern, C.B. 1993. Potential response of Pacific Northwestern forests to climate change, effects of stand age and initial composition. *Climatic Change*, 23:247-266.
- Van Sickle, J.; Gregory, S.V. 1990. Modeling inputs of large woody debris to streams from falling trees. *Canadian Journal of Forest Research*, 20:1593-1601.
- Wong, C.; Dorner, B.; Sandmann, H. 2003. Estimating historical variability of natural disturbances in British Columbia. *Land Management Handbook 53*, BC Ministry of Forests and BC Ministry of Sustainable Resource Management, Victoria, BC.
- Zavoianu, I. 1985. Morphometry of drainage basins. *Developments in Water Science*, 20, Elsevier, Amsterdam.





Contact:

For more information on the Canadian Forest Service, visit our web site at:
cfs.nrcan.gc.ca

or contact the Pacific Forestry Centre
506 West Burnside Road
Victoria, BC V8Z 1M5
Tel: (250) 363-0600 Fax: (250) 363-0775
cfs.nrcan.gc.ca/regions/pfc



To order publications on-line, visit the Canadian Forest Service Bookstore at:
bookstore.cfs.nrcan.gc.ca